Argonne NATIONAL LABORATORY

Heavy Vehicle Drag Estimation using Commercial CFD Tools

Heavy Vehicle Systems Optimization Program Review
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Energy Efficiency and Renewable Energy

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EERE FreedomCAR and Vehicle Technologies Program

Outline

- Purpose and Goals
- Timeline
- Approach
- Computational Platforms
- Successes
  - Generalized Conventional Model
- Current Efforts
  - Generalized Conventional Model
  - CRADA with PACCAR
  - CRADA with Caterpillar
  - Aerovolution Inflatable Boattail
- Future Efforts
  - Combined Underhood and External Aerodynamics
  - Transfer of Aerodynamic Lessons Learned to PSAT

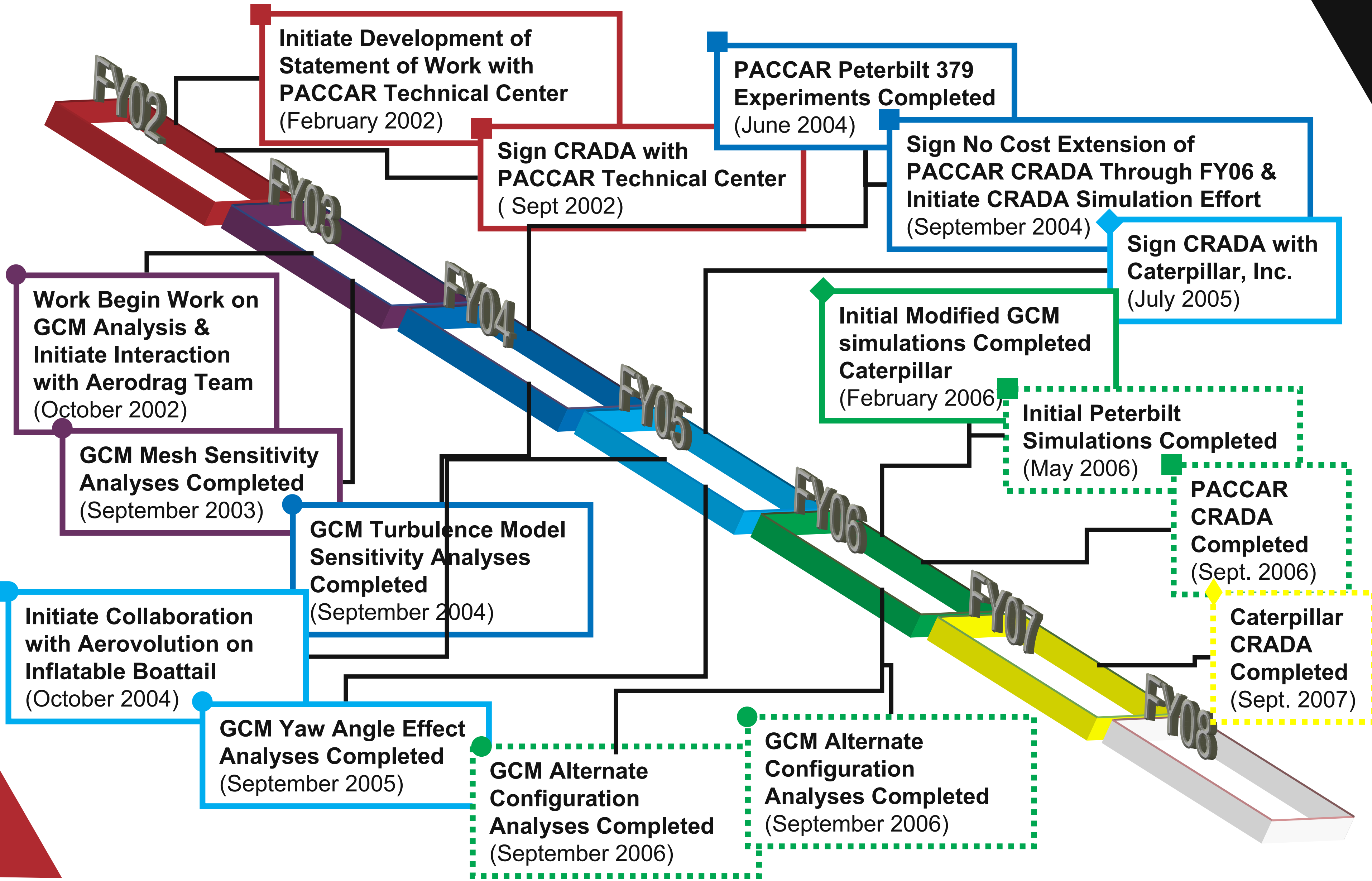
Purpose and Goals

- Purpose
  - Enable near-term improvements in tractor-trailer fuel economy through signficant reductions in parasitic losses resulting from aerodynamic drag
    - *Identify near-term opportunities for incorporation of high-quality numerical simulation using commercial tools into design cycle of tractor-trailer systems*
- Goals
  - Provide independent assessment of current generation commercial CFD for heavy vehicle aerodynamic simulation
  - Provide guidance for simulation of tractor-trailer geometries using commercial CFD tools
  - Demonstrate that “lessons learned” for generalized or simplified truck geometries are applicable to real truck geometries

Industry Collaboration

- **Establish industry collaborations**
  - Provide “real world” focus
  - Accelerate transfer of lessons learned to manufacturers
- **CRADA with PACCAR Technical Center**
  - Funding: DOE - $180K, PACCAR - $180K (in kind)
  - Signed September 2002, work and spending delayed until experiments completed in June 2004
  - Collaborate on validation of capability for realistic geometries
- **Collaboration with Aerovolution**
  - Initiated October 2004
  - Provide geometric data for realistic add-on inflatable boattail device
- **CRADA with Caterpillar**
  - Funding (proposed): DOE - $200K, Caterpillar - $200K (in kind)
  - Signed July 2005
  - Collaborate on evaluation of potential impacts of Advanced Electric Truck developments on aerodynamic drag

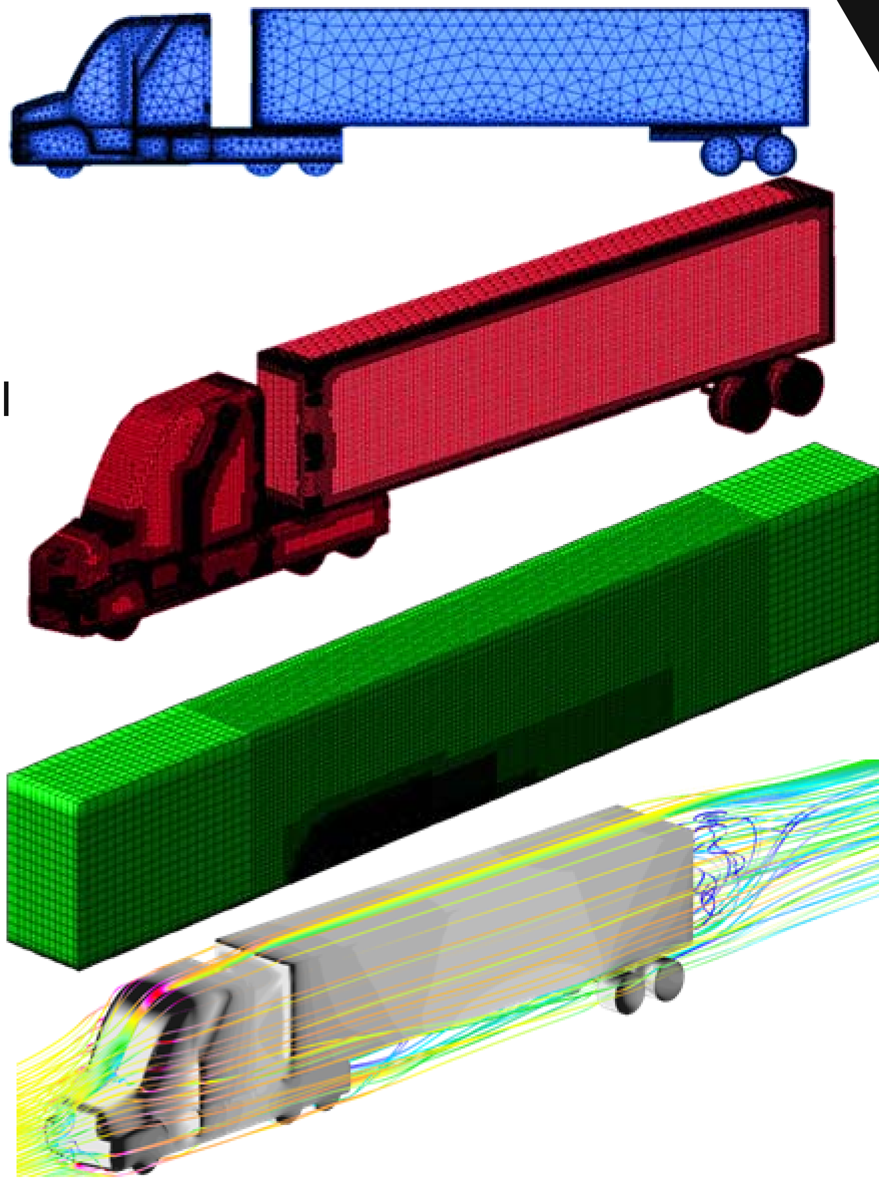
Timeline



FY02
FY03
FY04
FY05
FY06
FY07
FY08
Initiate Development of Statement of Work with PACCAR Technical Center (February 2002)
Sign CRADA with PACCAR Technical Center (Sept 2002)
Work Begin Work on GCM Analysis & Initiate Interaction with Aerodrag Team (October 2002)
GCM Mesh Sensitivity Analyses Completed (September 2003)
PACCAR Peterbilt 379 Experiments Completed (June 2004)
Sign No Cost Extension of PACCAR CRADA Through FY06 & Initiate CRADA Simulation Effort (September 2004)
GCM Turbulence Model Sensitivity Analyses Completed (September 2004)
Initiate Collaboration with Aerovolution on Inflatable Boattail (October 2004)
Sign CRADA with Caterpillar, Inc. (July 2005)
GCM Yaw Angle Effect Analyses Completed (September 2005)
Initial Modified GCM simulations Completed Caterpillar (February 2006)
Initial Peterbilt Simulations Completed (May 2006)
PACCAR CRADA Completed (Sept. 2006)
GCM Alternate Configuration Analyses Completed (September 2006)
GCM Alternate Configuration Analyses Completed (September 2006)
Caterpillar CRADA Completed (Sept. 2007)

Approach

- Generate Computational Models from CAD data
- Use automatic meshing tools in Star-CD's Aerodynamics Expert System, ES-Aero
  - Generate new "wrapped" surface mesh
  - Create subsurface
  - Trim geometry from a grid of hexahedral blocks
  - Extrude mesh back to original surface
- Simulate fluid flow over vehicle surface using standard solver options within the Star-CD code
  - SIMPLE solution algorithm with conjugate gradient solver
  - Second order MARS differencing for momentum and mass equation
  - First order upwind differencing for turbulence equations
  - Steady RANS turbulence models with wall functions

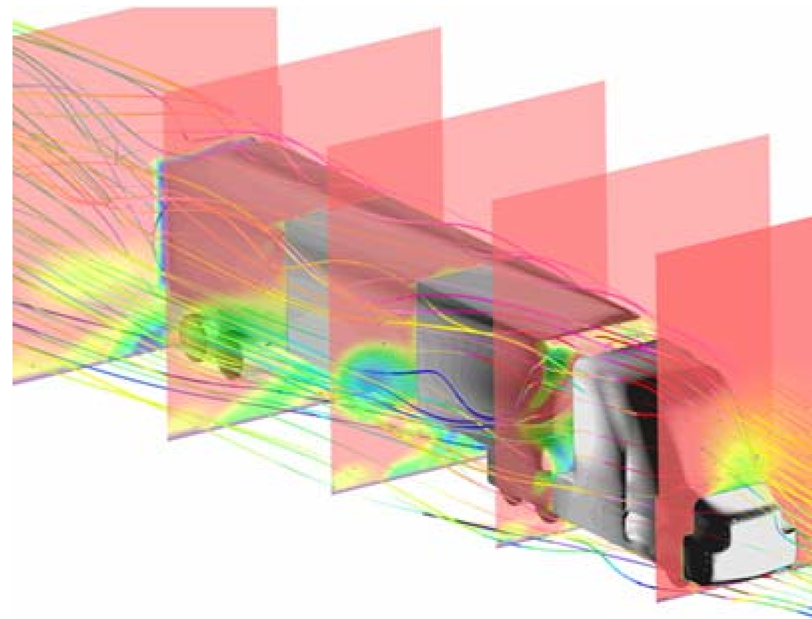


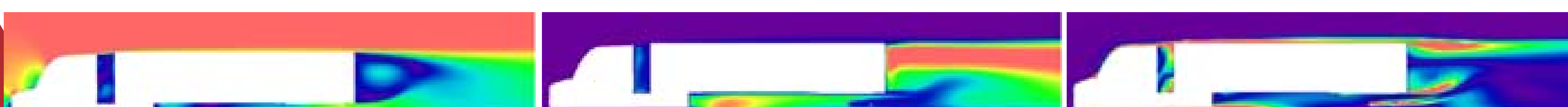
Computational Platforms

- Front ends
  - 64-Bit Itanium2 workstation
    - *Dual 2.4 GHz processors w/24 GB RAM shared*
  - 64-Bit Xeon EM64t workstation
    - *Dual 3.2 GHz Processors w/8 GB RAM shared*
- RESERV Linux Cluster
  - Heterogeneous Linux cluster
    - *75 single P4 processor nodes*
      - 3.2 GHz Processors
      - 2 GB RAM per node
      - 1 GBit/second network
    - *~ 2 TB of disk storage*
  - Typically use 8-32 nodes for aero simulations
- JAZZ Linux Cluster
  - Homogeneous Linux cluster
    - *240 single 2.3 GHz Xeon processor nodes*
      - 1 GB Ram
    - *60 dual 2.3 GHz Xeon processor nodes*
      - 4 GB Ram (shared)
    - *1 GBit/second networking*
    - *~100 TB of disk storage*

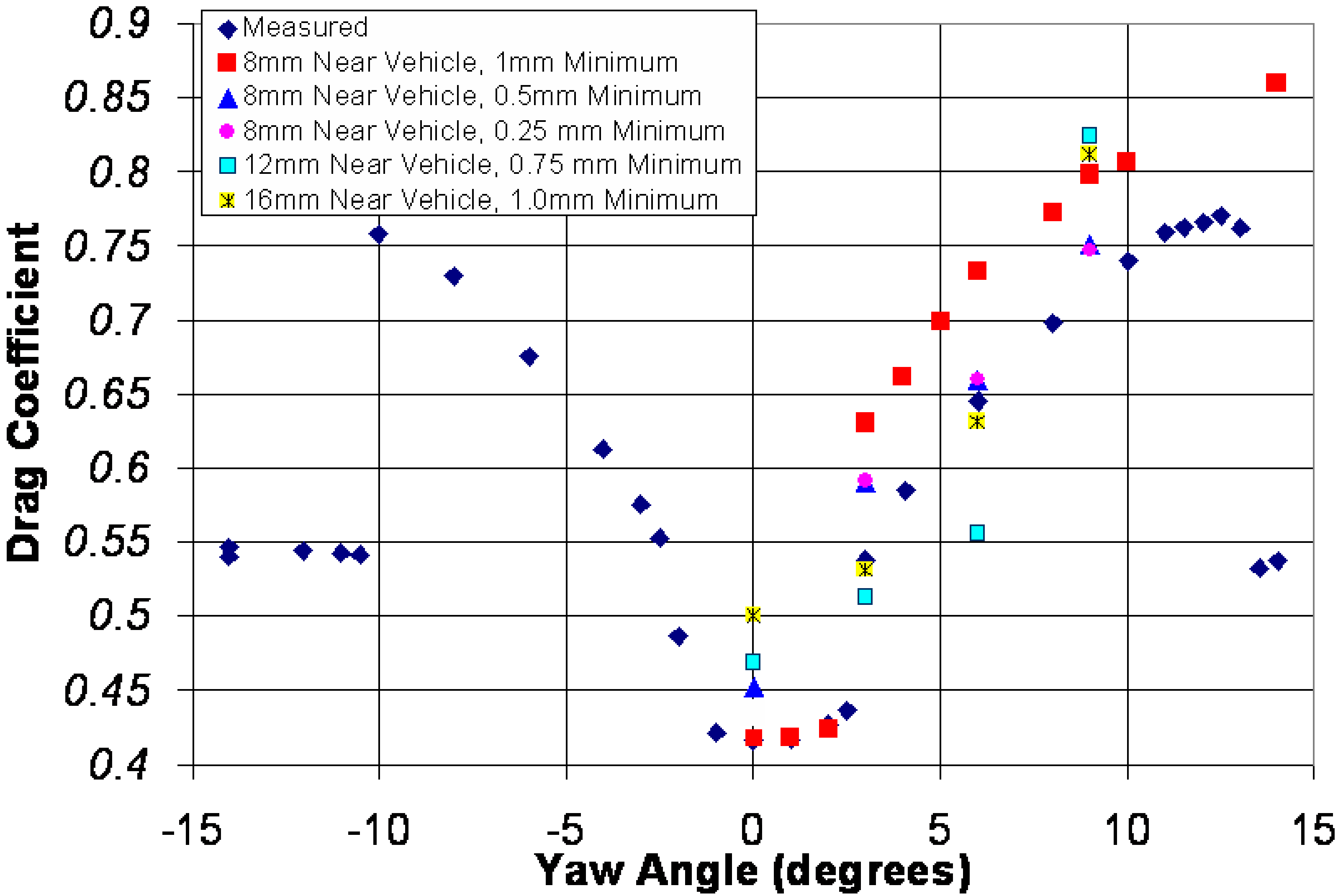
Successes - GCM

- Demonstrated applicability of commercial CFD tools to simplified tractor geometries
  - Predict drag coefficients for un-yawed Generic Conventional Model (GCM) within 1 percent of value measured in 1/8th scale wind tunnel experiments
    - *Using approximately 8 million cells*
    - *Mesh generation steps require ~8 hours*
    - *Simulation requires ~200 CPU hours Simulation can be completed in ~8 hours using 32 2.3 GHz processors with 1GB of RAM each*
  - Predict drag coefficients for GCM at low yaw angles within 1-3 percent for models of similar size
  - Predict drag coefficients for GCM at high yaw angles within 5-7 percent for models of similar size



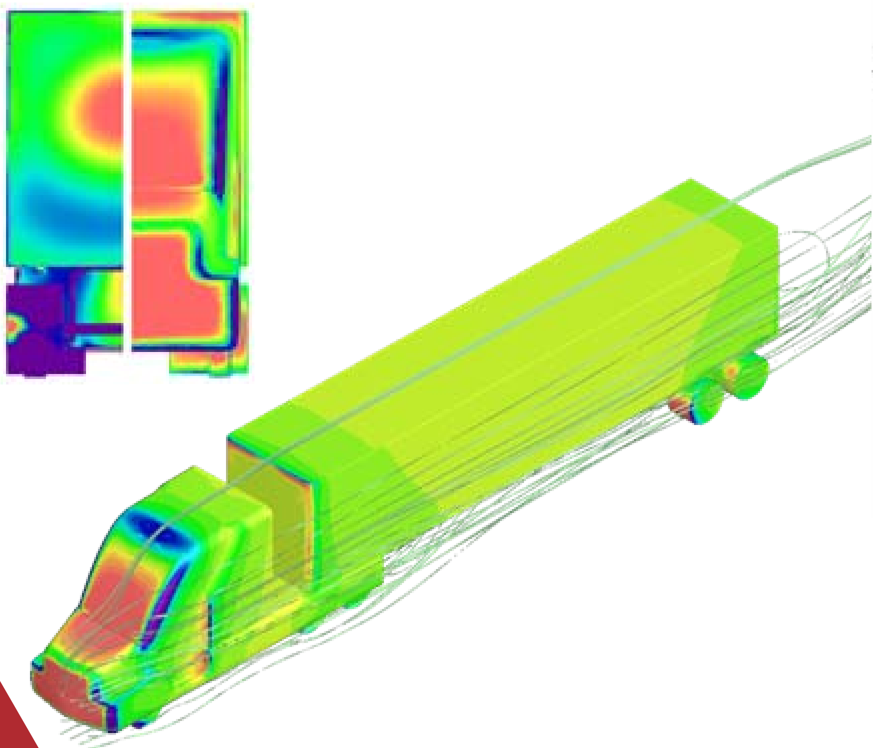


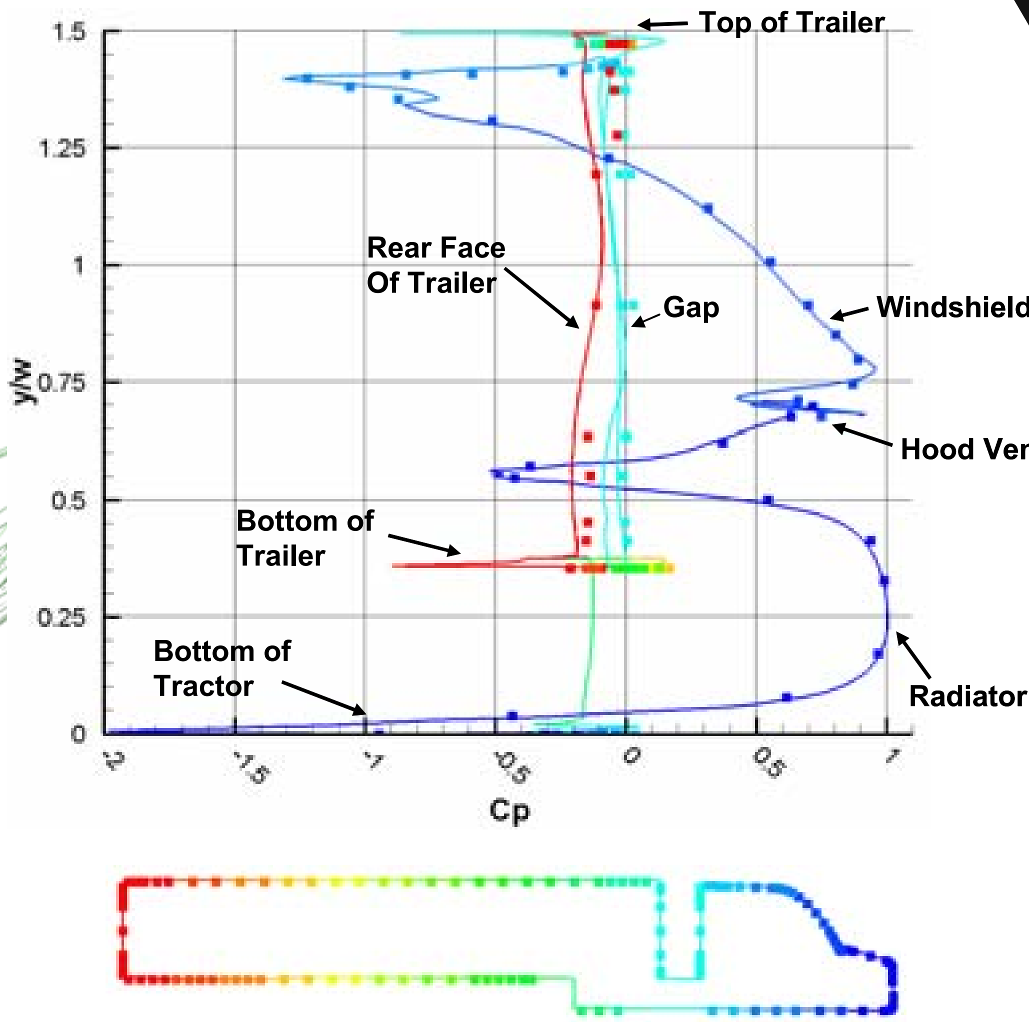
Successes – GCM (drag)



Successes – GCM (surface pressure)

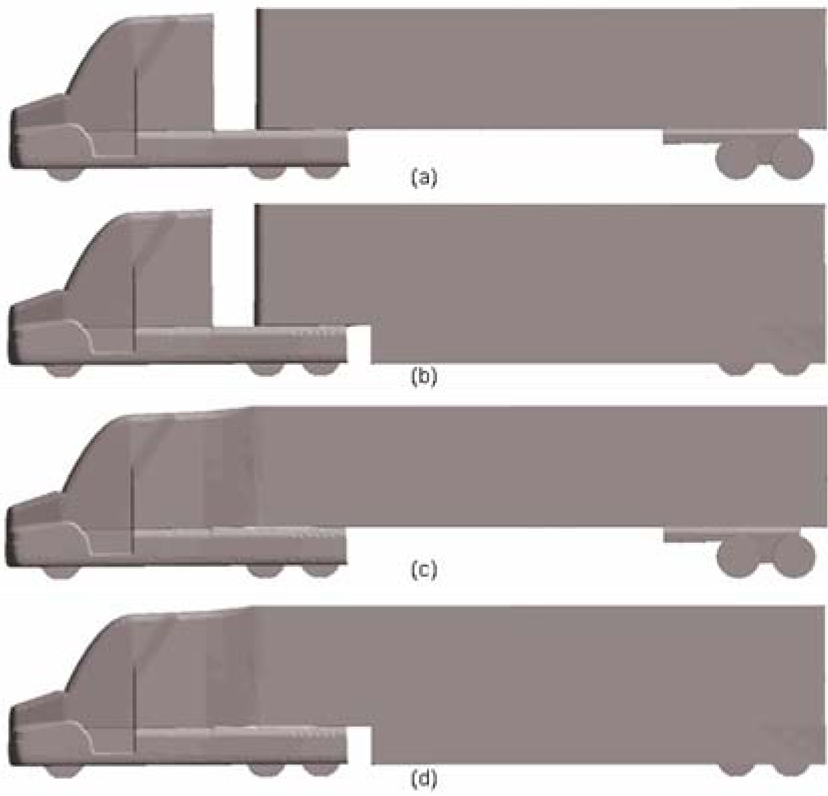
- Drag comparisons alone are not sufficient to call an approach validated
- Compare simulations with detailed surface pressure measurements





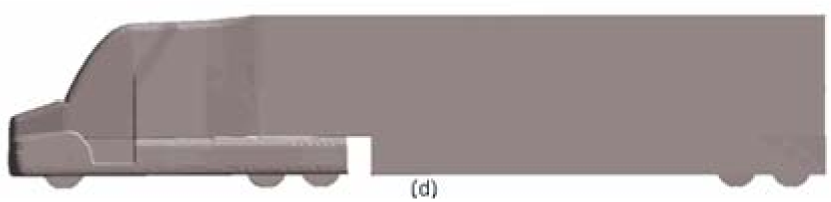
Current Efforts – GCM Drag Delta Prediction

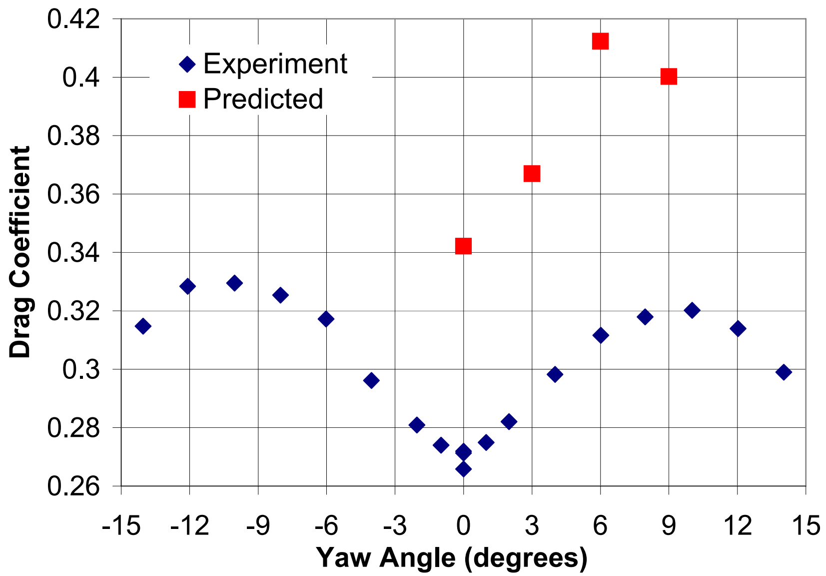
- Evaluate applicability of commercial tools for prediction of changes in aerodynamic performance with changes in geometry
- Data available from initial GCM experiments in NASA Ames 7'x10' tunnel for several alternate GCM configurations
- First consider configuration with belly box + full gap fairing
  - Mimics simpler GTS configuration
  - Low drag coefficient
  - Maximize importance of accurately predicting base drag



Current Efforts – GCM Drag Delta Prediction

- Apply process developed for analysis of standard configuration to alternate configuration
  - Repeat for yaw angles of 0,6,3 degrees
- Initial Results
  - Drag is over-predicted by approximately 25%
  - Calculations reach the same level of convergence, but require approximately 25% more iterations to reach that level
  - Average value of y+ is lower than for standard configuration although thickness of wall cells is maintained
    - *Wall functions may not be correctly applied to current model*





PACCAR CRADA

PACCAR CRADA

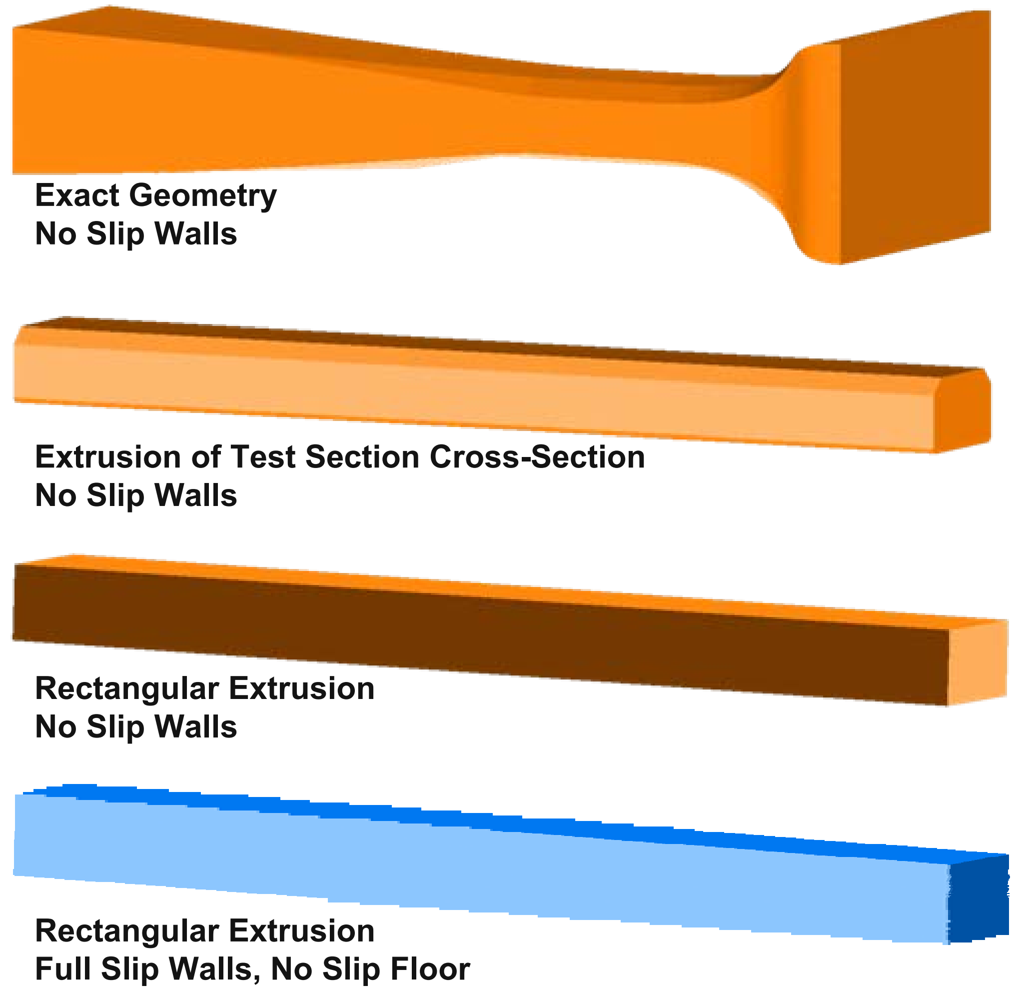
- CRADA Signed September 2003 between ANL and PACCAR Technical Center
- Goals:
  - Confirm applicability of guidelines to real truck geometry as part of industrial design cycle
  - Provide confidence in numerical simulation technologies to encourage use of CFD in tractor-trailer design cycles
  - Transfer lessons learned to industrial partners

PACCAR CRADA - Experiments

- Experiments were completed June 2004
  - University of Washington Wind Tunnel
    - *Roughly same cross section as NASA Ames 7'x10' tunnel*
    - *Recorded standard aerodynamic forces and moments*
    - *Recorded surface pressures at 128 locations*
  - Yaw Angle Sweeps
  - Configuration Changes
    - *Gap width*
    - *Accessories removed*
      - Visor
      - Air coolers
      - Mirrors
      - Exhaust Stack

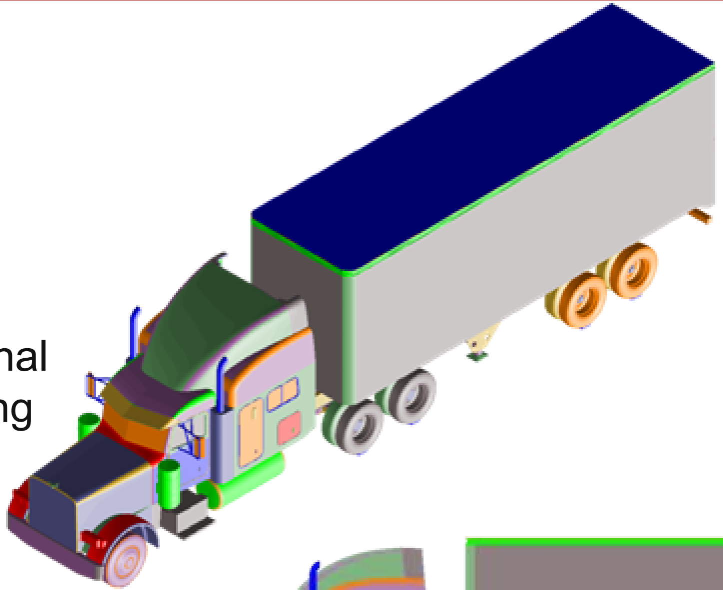
PACCAR CRADA – Empty Tunnel Simulations

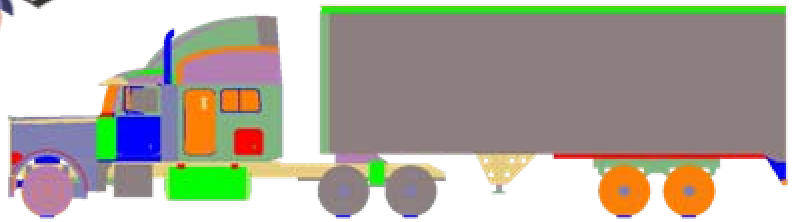
- Determine if exact wind tunnel geometry must be modeled
  - Prefer to use a rectangular box with the same primary dimensions
    - *put more cells where they matter most – ON THE VEHICLE SURFACE*
- Compare predictions of axial and radial velocity distributions in exact wind tunnel geometry with predictions for three simplified geometries
- Acceptable approximation provided by a rectangular extrusion which
  - maintains the cross sectional area
  - Has no-slip conditions applied only to the floor in the region downstream of the vacuum plate used to remove the tunnel boundary layer just upstream of the model

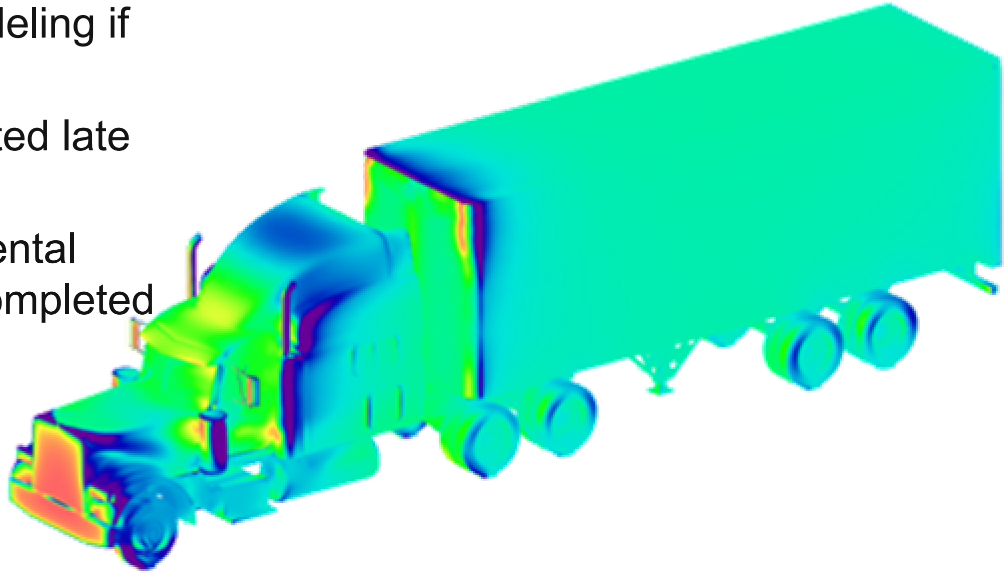


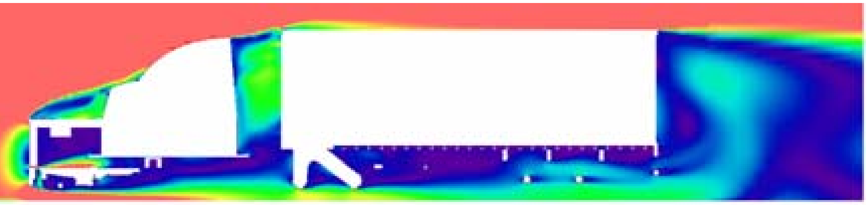
PACCAR CRADA Simulations

- Preliminary simulations completed in early FY05 allowed development of a computational simulation matrix which identifies all modeling options to be considered
  - Mesh sensitivity
  - Turbulence model sensitivity
- Verified applicability of Star-CD software to very large models containing 75-100 million cells on Jazz Linux Cluster
  - May be needed for turbulence modeling if wall functions are not used
- All identified simulations will by completed late Spring 2006
- Results will be compared with experimental data when all simulations have been completed









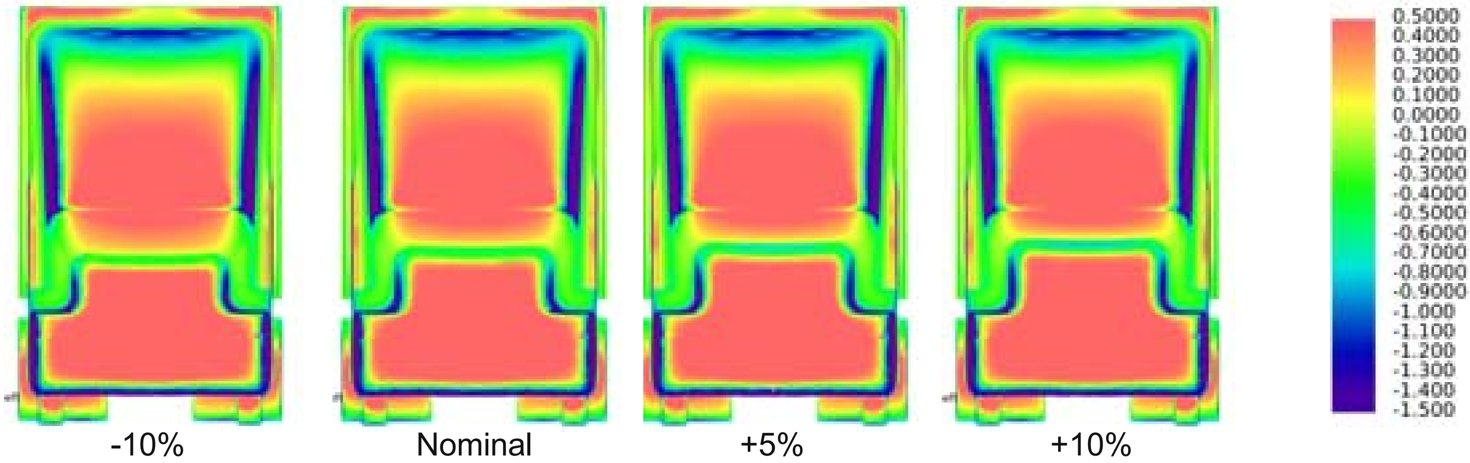
Caterpillar Crada

Caterpillar CRADA

- ANL and Caterpillar, Inc. signed CRADA Agreement in September 2005
  - ANL is a partner in Caterpillar's effort to develop advanced electric systems for heavy duty trucks
- Goals:
  - Provide means of improving engine heat rejection through electrification of underhood components
  - Eliminate need to increase size of radiator to meet 2007 emissions restrictions
- Argonne will provide
  - Assessment of effect of changing the radiator area of a simplified tractor-trailer on aerodynamic drag coefficient
    - *Changes in height*
    - *Changes in width*
    - *Changes in total area*
  - Assessment of potential impact of including underhood flow on drag coefficient predictions
  - Assessment of aerodynamic characteristics of final project geometry, possibly including flow through underhood if deemed necessary

Caterpillar CRADA
Current Progress

- Developed four modified simplified tractor trailer models based on GCM geometry for evaluation of the impact of changing the radiator height
  - Fully Symmetric Nominal Model
  - 10% Reduction in Radiator Height
  - 5% Increase in Radiator Height
  - 10% Increase in Radiator Height
- In all cases, only the radiator height and hood pitch are modified. All other dimensions are maintained.



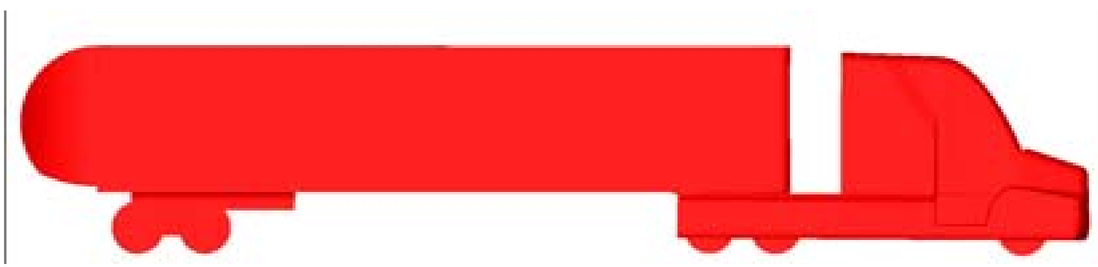
Surface Pressure Coefficient

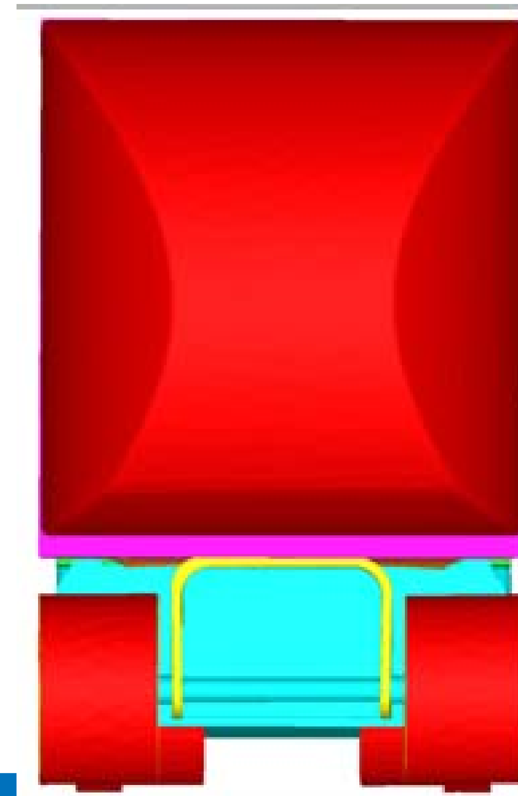
Caterpillar CRADA
Current Progress

Aerovolutions Interactions

Aeroworks Inflatable Boattail

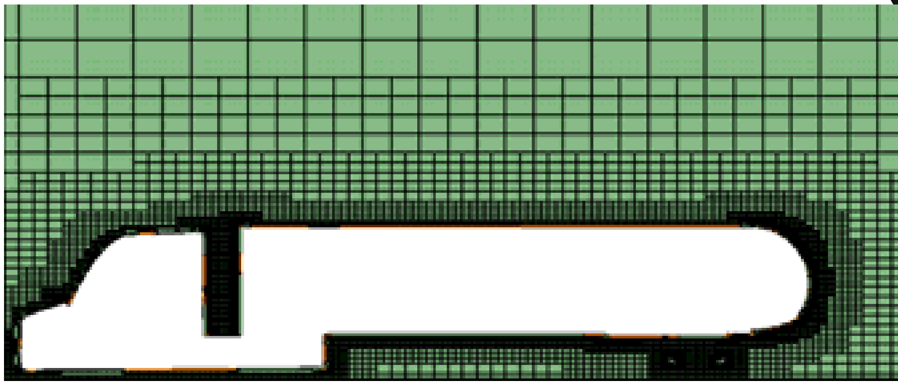
- Approached by Aerovolution seeking guidance on CAE of inflatable boattail device
- CAD Data describing Inflatable Boattail shape provided by Aeroworks
- Boattail scaled to fit GCM
- Integrated GCM model with Boattail developed
- Preliminary Sensitivity study
  - Near vehicle cell size
    - *12 mm and 8 mm*
  - Near wall cell size (for 8mm case)
    - *1 mm and 0.5 mm*

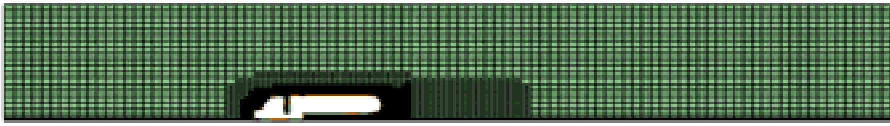




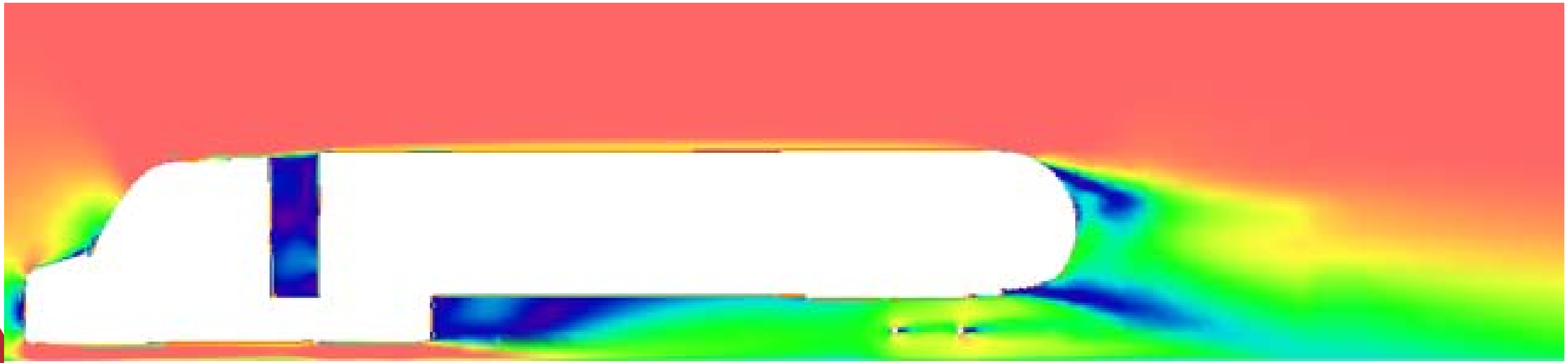
Aerovolution Inflatable Boattail

Near Vehicle Cell Size	Near Wall Cell Size	Drag Coefficient
12 mm	2 mm	0.4179
8 mm	1 mm	0.4116
8 mm	0.5 mm	0.3975



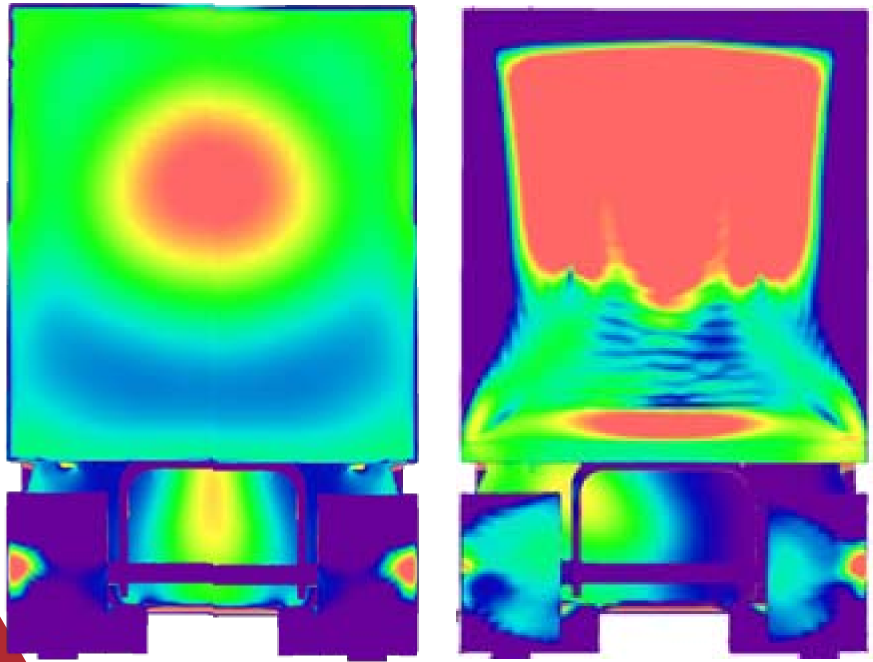


- Device Reduces Drag Coefficient by approximately 7%
  - Compared with GCM simulation with comparable mesh density



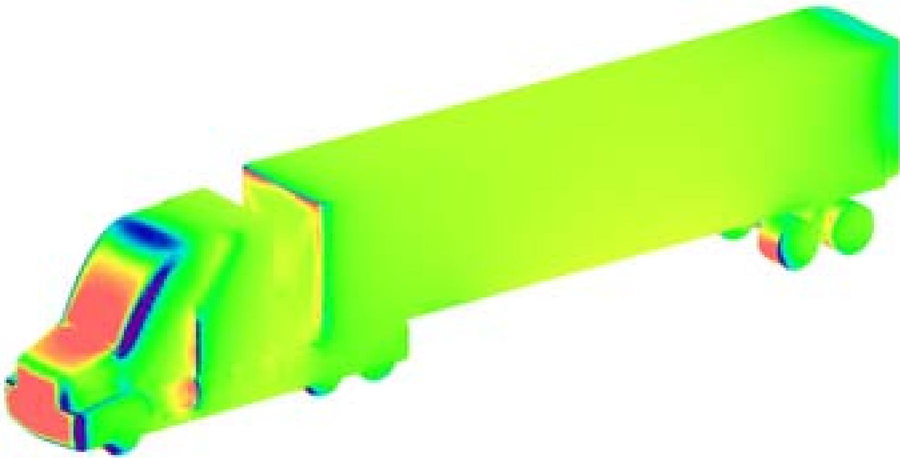
Aerovolution Inflatable Boattail

- Comparison of pressure distribution reveals that total surface area exposed to positive pressures (shown in red) on trailer base increases when device is used.
- However, Negative pressures tend to become more strongly negative when device is used
  - Optimization may improve fuel savings



Nominal

With Device



Future Focus

- **Contributing to development of aerodynamic drag reduction devices**
  - Pursue collaborative opportunities with Aerovolution
  - Collaborate with Aerodrag team and OEM's to evaluate other device designs
- **Extending validation of capability to integrated external aerodynamics and underhood flow modeling**
  - Increasing heat rejection demands require accurate representation of flow through radiator and the engine compartment
- **Providing data for improvement of aerodynamic models included in powertrain and integrated system analysis codes, such as PSAT (Powertrain Systems Analysis Toolkit)**
  - Initial yaw angle dependence function provided in late February 2006 to enable code development
  - Will work with PSAT developers to provide options for incorporation of additional modeling options when initial extended aerodynamics modeling capability has been implemented

Conclusions

- Demonstrated applicability of commercial tools for prediction of aerodynamic characteristics of simplified tractor trailer geometries
- Drag coefficients may be predicted with reasonable accuracy, but surface pressure distributions should also be considered in evaluation of predictive accuracy
  - Particularly important for development of gap or wake flow devices
- Completing simulations which will provide the basis for an assessment of the applicability of these tools as part of CRADA with PACCAR Technical Center
- Initiating effort to evaluate applicability for predictions of changes in aerodynamic coefficients resulting from isolated design changes.
- Beginning to apply tools and lessons learned to development of strategies and devices for reduction of aerodynamic losses and improvement of fuel economy

Summary

- **Relevance to DOE Objectives**
  - Class 8 trucks account for 11-12% of total US petroleum consumption
  - 65% of energy expenditure is in overcoming aerodynamic drag at highway speeds
  - 12% increase in fuel economy is possible and could save up to 130 midsize tanker ships per year
- **Approach**
  - Assess capabilities in commercial Computational Fluid Dynamics software for immediate application by tractor OEM's and device developers
  - Collaborate with aerodrag team to provide detailed assessment of predictive capabilities using extensive data available from NASA's Generic Conventional Model experiments
  - Collaborate with industry to insure that lessons learned are applicable to real world problems
- **Accomplishments**
  - Demonstrated that drag coefficients can be calculated within 1-3% for the GCM at low yaw angles and within 5-7% at high yaw angles
  - Working with PACCAR Technical Center to confirm that the approach can be extended to real trucks
  - Working to evaluate whether the approach enables prediction of changes in drag with similar accuracy.
- **Technology Transfer/Collaborations**
- • Multi-Lab (LLNL, ANL, SNL, NASA, GTRI), multi-university (USC, Caltech, UTC, Auburn) effort with NRC-Canada
- • Industry
  - Vehicle Aero - PACCAR CRADA, Caterpillar CRADA
  - Devices – Aerovolution
- **Future Directions**
  - Collaborate in the application of the capability to development and design of devices with improved performance and operational characteristics
  - Extend capability to combined underhood and aerodynamic simulation to meet OEM's need for future changes in EPA regulations
  - Provide improved aerodynamic modeling functions to powertrain simulation codes such as PSAT